Ballistic Perforation of Graphite/Epoxy Composite

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Special Report 96-29

**US Army Corps
of Engineers**
Cold Regions Research &
Engineering Laboratory

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PREFACE

Ballistic Perforation of Graphite/Epoxy Composite

PIYUSH K. DUTTA, DENNIS FARRELL, SUSAN TAYLOR, AZIZ TADAYON AND DAVID HUI

INTRODUCTION

The response of advanced composite laminated plates under projectile impact has been studied extensively in recent years, but because of the presence of a large number of fracture modes and of the complex response of the constituent materials to the extremely high strain rate, the process has not been completely understood. Although the penetration event occurs in a matter of only several microseconds, the constitutive properties of the constituent materials of the composite under such high strain rates change drastically. The general objective of the current investigation was to evaluate the influence of the laminate character-istics and the impact velocities on the penetration response of these composites. More specific objectives include development of a methodology to characterize and analyze post-penetration fracture surfaces both in macro- and in micro-scale. Earlier work conducted by Altamirano (1991) and Mayer* (Fig. 1) demonstrates an empirical relationship between the energy absorption function E and the impact velocity V as:

$$E = CV^n \tag{1}$$

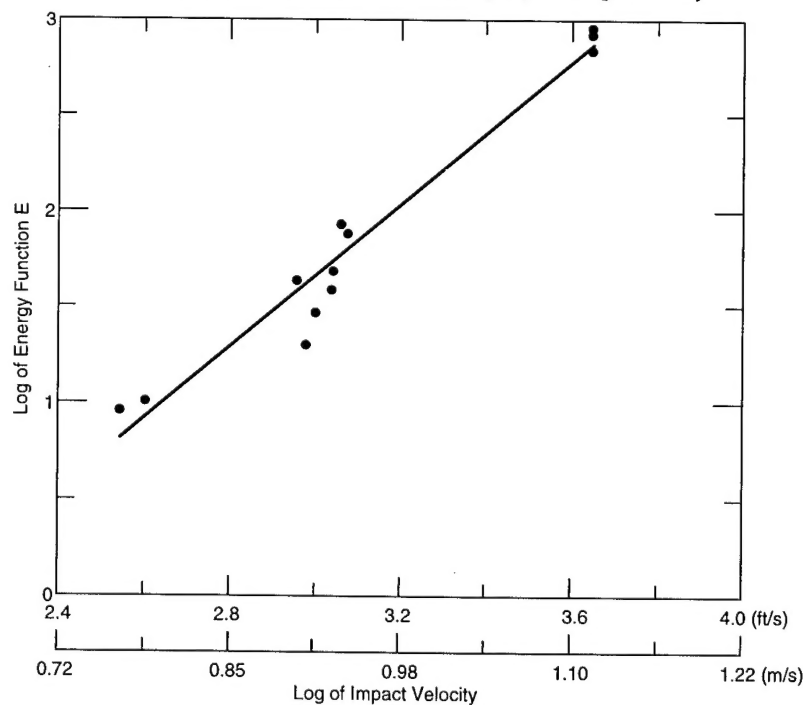where C is a constant depending on the laminate and projectile geometry.

Figure 1. Ballistic test results of 31-ply Gr/Ep plate 12.7-mm steel sphere impact.*

The work was conducted with ballistic perforation impact at CRREL. An energy analysis of this work presented earlier by Hui (1993) shows that the fracture surfaces of fragments produced from the impact of single-ply and 30-ply plates by 12.7-mm (0.5-in.) steel spheres could be related to the various mechanisms of energy absorption. However, the experimental details and systematic microscopic examination were not documented by Hui. The purpose of this report is to document those experimental details and the microscopic analysis. We will also elaborate on the theory of energy absorption under a penetrating and perforating projectile at greater depth using our experimental data.

MATERIALS

The tests were performed on two batches of Gr/Ep (graphite/epoxy) plates. The first batch consisted of eight plates each 8-ply thick and was made of T-300 graphite fiber reinforcement in Fiberite 984 epoxy resin. All fibers were oriented in one direction. Size of each plate used for testing was 12×12 in. (30×30 cm). The second system was a 30-ply AS-4/3502 laminate with a stacking sequence of

$$[(\pm 45/0_2)_2 \, / \, 90 \pm 45/0_2/\pm 45]_s.$$

This material was supplied by the U.S. Air Force Wright Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio, in the sizes of 4.5×4.5 in. (11.4×11.4 cm). The above stacking sequence gives the laminate a quasi-isotropic property, as opposed to the unidirectional (or anisotropic) property of the batch 1 material.

BALLISTIC TESTS

Ballistic test facility

The CRREL Terminal Ballistic Facility (TBF) is shown schematically in Figure 2a and in an assembly photograph in Figure 2b. The entire facility is located in four adjoining rooms: the firing room, the control and instrumentation room, loading room, and the cold target room. The firing room is lined with a 20-cm-thick concrete wall. The room is equipped with a 14.3-mm ($^9/_{16}$-in.) bore, explosive-powered gun that can be remotely operated from the control room. The barrel end and the projectile path are completely sealed with a 127-mm- (5-in.-) i.d. steel pipe, which passes through the wall of the firing room into the target room. The target room can be refrigerated to a temperature of –25°C (–13°F). The end of the seal pipe terminates into a specially designed plexiglass chamber (Fig. 2b). It is equipped with two metallic holding plates to clamp the composite target test plates at the periphery for normal impact. The target test chamber is connected to a back-chamber of the same diameter and length, and also it is completely sealed to maintain interior vacuum when needed. The back-plate of the chamber, made from plastic, is replaceable after every shot. The projectile exiting through the back-plate is captured by a sandbox located in the flight path opposite to an opening in the wall. For high velocity (>610-m/s, 2000-ft/s) tests the interior of the gun barrel, seal pipe and the test chamber must have a very high vacuum pressure, which is achieved by connecting the pipe interior to a vacuum pump. For low velocity tests no vacuum is necessary.

The building is also equipped with a remote firing circuit. Red, flashing warning lights are located on the outside of the building and all rooms except the loading room. These warning lights, the illuminating lights in the range area, and door switches on each entrance to the range are integral components of the remote firing circuit. The design of the remote firing circuit was made such that the following three conditions must be met to complete the circuit and fire the gun:

1. The illuminating lights in the range area must be off.
2. The red lights must be on and flashing.
3. Both doors to the range must be closed.

It is only when those conditions are met that the remote firing controls in the instrumentation room can be activated.

Projectiles

To make this study compatible and complementary to the projectile perforation studies that were being conducted at the Air Force Wright Laboratory, 12.7-mm- (0.5-in.-) diam. hardened steel sphere projectiles were selected for the series of tests. The firing device has been designed to ride on two horizontal rails through four Thomson linear bearings. By varying the friction between the bearings and the rails, the length of recoil is controlled. The firing circuit works through a 42-V DC push type solenoid valve. The valve, mounted beneath the carriage, activates a trigger mechanism through a switching device in the instrumentation room. The impact and exit velocities were measured using light-activated chronograph screens in
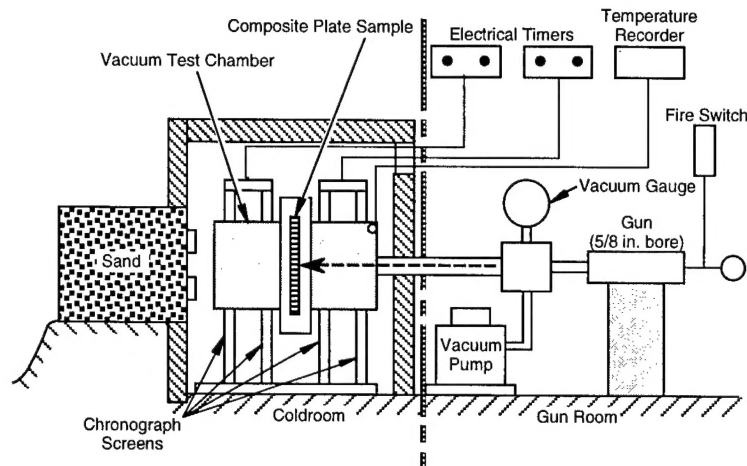
a. Schematic of ballistic test facility.
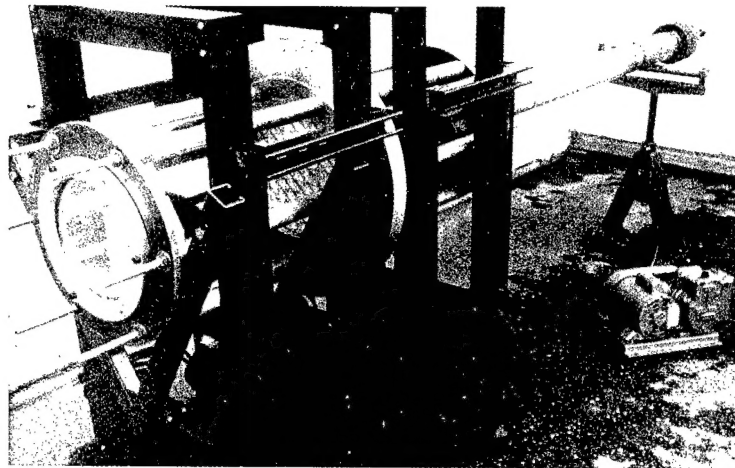
b. Assembly of the ballistic test gun system.

Figure 2. CRREL ballistic test facility and gun system.

pairs on both sides of the target. The output from the chronograph screen starts and stops a timer with 10^{-7} second accuracy.

All tests were performed using 12.7-mm- (0.5-in.-) diam. hardened steel sphere projectiles. The projectile is first located in the gun with a suitable sabot (a winged plastic receptacle) to guide the sphere through the gun barrel without any appreciable loss of firing pressure of the explosive powder. The amount of gun powder necessary to propel the projectile at the desired velocity was first determined by trial runs. These trials established the relation between the quantity of gun powder and the projectile velocity. The actual velocities of the projectile before impacting the target and after exiting from the target were also measured by a set of light-activated chronograph screens. When the projectile crosses the light path

of the first chronograph screen, it starts the counting clock. When it passes the next one, the signal from it stops the counting, thus displaying the time of travel on the time counter. By measuring the distance between the two light screens, the projectile velocity is calculated.

No attempt was made to capture the fragments from the impact on the unidirectional composite. The focus of the unidirectional composite impact test was to identify the gross damage pattern developed on the composite. The fragments from the quasi-isotropic composites were collected on the adhesive coated papers that lined the interior of the target chamber on both the impact and exit sides. Figure 3 shows one typical perforated plate of unidirectional Gr/Ep, and Figure 4 shows a carefully cut section through the 30-ply quasi-isotropic Gr/Ep.
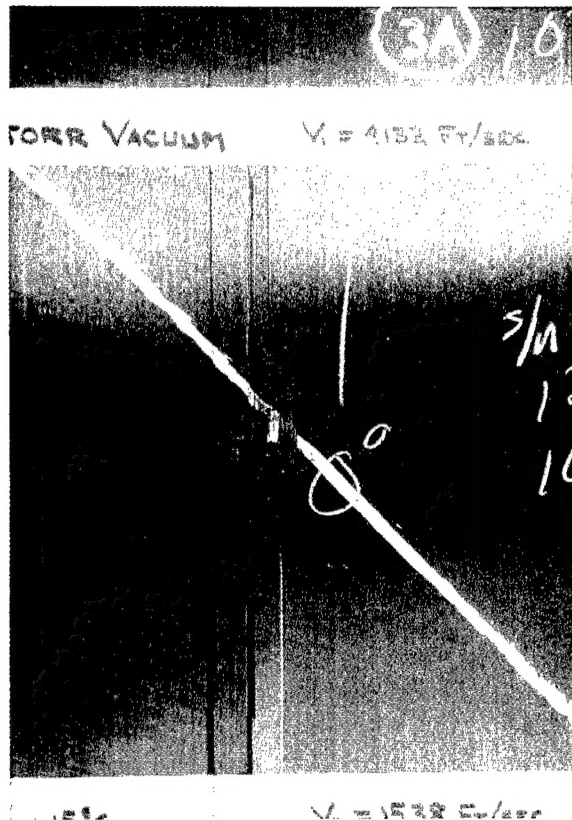
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Figure 3. *Typical specimen of the unidirectional Gr/Ep specimen after test.*

Figure 4. *Section of a 30-ply Gr/Ep panel through the perforation.*

DAMAGE ANALYSIS

The damage in the unidirectional laminate was simple to interpret. Because of severe anisotropy of the stiffness and strength properties, only longitudinal cracks in fiber direction propagated. The primary failure in the impact zone was obviously indentation followed by fiber breakage, delamination, and finally shear plugging. Numerous longitudinal cracks split the specimens in a large number of longitudinal strips (Fig. 3). Figure 5 shows the effects of velocity on the damage process of the unidirectional Gr/Ep. Notice that the shear plug-out hole for the high-velocity impact (approx. 4500 ft/s or 1400 m/s) has a much cleaner outline (Fig. 5a) than the one at lower velocity (Fig. 5b). It seems likely that at higher velocities more momentum is trapped in the shear plug than at low velocities. At lower velocities the fibers break upon impact of the projectile, and then flex with shear failures propagating longitudinally to the boundaries of the specimens.

Figure 6a shows a very low velocity (88.4-m/s, 291-ft/s) impact of the steel ball on the 30-ply Gr/Ep laminate. The energy of impact in this case was not sufficient to cause perforation. (Ballistic tests performed at the U.S. Air Force Wright Laboratory [*] show that the V_{50} velocities for this type of laminates would be about 137 m/s [450 ft/s].) Nevertheless, damage by delamination and fiber breakage did happen as evident from the slight bulging of the rear surface and an ultrasonic scanning (C-scan) examination performed on this laminate. At velocities around V_{50} a typical damage looks like the one shown in Figure 6b, which was obtained at 151 m/s (496 ft/s). The perforation was complete in this case. The high velocity (975-m/s, 3200-ft/s) perforation type damage on these laminate was rather extensive. Figure 4 shows a cutout section through the perforation hole of the high velocity impact. The cutout was carefully made without disturbing the positions of broken lamina and fibers. Notice that the damages on both impact and exit sides are more extensive than at the center. Delamination damage is more in the rear side, whereas the impact end has more crushing and fiber breakage.

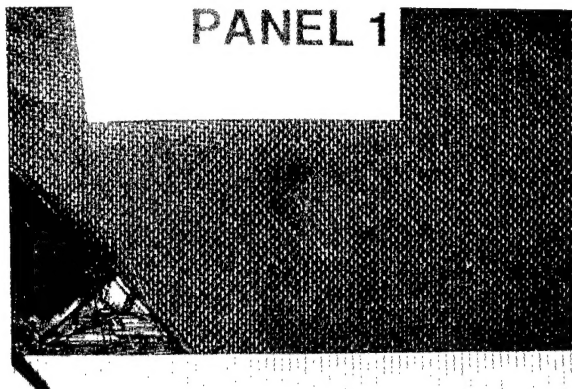[*] A. Mayer, U.S. Air Force Wright Laboratory, personal communication, 1992

a. High velocity: shear plug out.   *b. Low velocity: no shear plug-out.*

Figure 5.Effect of velocity on the damage of unidirectional Gr/Ep plates.

a. Low velocity impact damage (unperforated).   *b. High velocity impact damage (unperforated).*
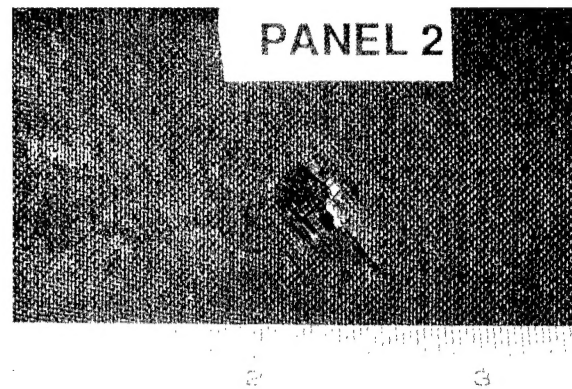
Figure 6. Impact damages to quasi-isotropic composite plates.

SCANNING ELECTRON MICROGRAPH ANALYSIS OF BALLISTIC FRAGMENTS

As mentioned before, the composite fragments from the 30-ply Gr/Ep target panels were collected on the adhesive-coated paper, lining both the front and rear sides of the target test chamber. As expected more fragments were collected on the rear side. Most particles appeared to be of longitudinal shapes, indicating that fragmentation happened by crack propagation more in the direction of the fibers than across it. A few larger pieces seemed to contain interlaminar joint surfaces. Fibers oriented in 45° and 90° angles are clearly visible in these fragments. Many of the samples in this category of tests showed hackle marks (Fig. 7a, b).

DISCUSSION OF RESULTS

The results of nonperforated low-velocity impact, perforated low-velocity impact, and the perforated high-velocity impact manifest progressive

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a. Micrograph of sample A.

b. Micrograph of sample B.

Figure 7. Very high velocity impact fragment fracture surfaces.

failure mechanisms, one taking over the other, as the velocity increases. For example, in the nonperforated low velocity impact on the multiple-ply laminate, the Hertzian indentation was the major form of damage, whereas at higher velocities shear plug-outs with extensive compressive failure and delaminations were the main mechanisms.

The fractographic features and its relation to the failure are of interest. Very little information on the genesis of hackle mark formation is available in the composites literature, except that a large number of researchers have observed their presence related with brittle failure (Morris 1982, Richards-Frandsen and Naerheim 1983). It has been shown by Purslow (1986) that in static failure, the presence of the relatively stiff fibers increases the influence of shear stresses on the resin fracture and hackle mark development under such conditions will be suppressed. Figure 8, reproduced from the work of Dutta and Taylor (1989), shows almost a total absence of any hackle marks from transverse tensile fracture under quasistatic loading over the full thickness of a seven-ply AS-4/3501 laminate. However, Purslow observed that at relatively high strain rate of deformation and fracture, matrix cleavage and hackle formation are common. Thus,

hackle marks in fracture surfaces would primarily indicate an impact induced damage, and proliferation of hackle marks on our ballistic fragments clearly indicates this trend (Fig. 7 a, b).

The hackle marks present a periodic formation of sigmoidally shaped ridges and troughs running roughly parallel to the fiber direction and located in the matrix region between them. There is a spatial periodicity perpendicular to the direction of the fibers, which is the first suggestive observation. The second observation is that the wavelength of these hackle marks appears to increase as the distance between the neighboring fibers increase (Fig. 7a). The wavelength of the hackle mark is of the of the order of interfiber distance. Sometimes, the ridges appear to be canted at an angle to the fiber axis.

It is appropriate now to examine the phenomenon of wavelength proportionality to fiber spacing at some depth. Conceivably the wavelength proportionality to fiber spacing would result if it were associated with or determined by a disturbance that propagates in the plane of two adjacent fibers from one fiber surface to the other at a fixed angle to their length direction. Then this proportionality would be reflected back from the other
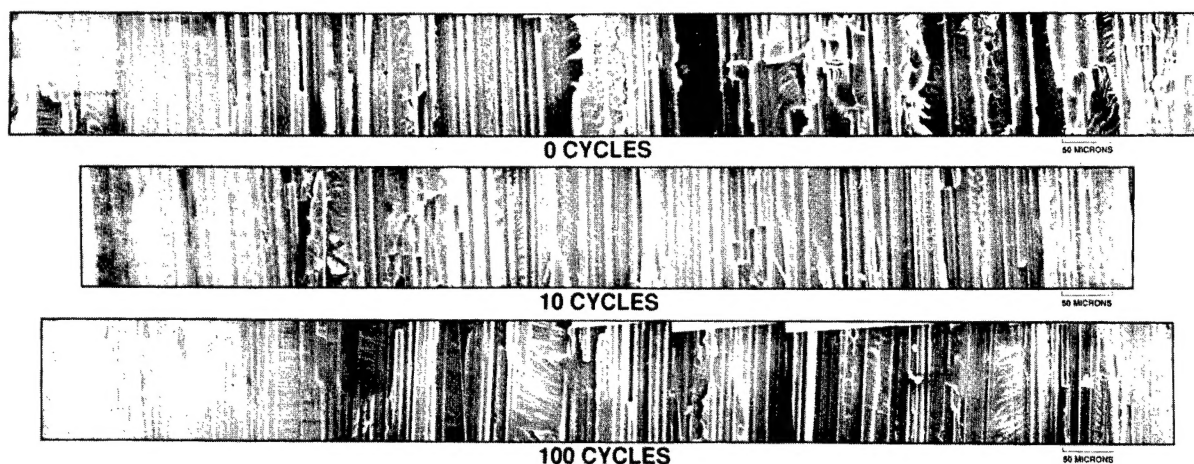
Figure 8. Scanning electron micrographs of a 7-ply AS-4/3501 laminate transverse fracture surface from static tension test after low temperature thermal cycling (Dutta and Taylor 1989).

fiber at an equal angle toward the first fiber, and the process then would be repeated. The distance between successive reflections from the same fiber then represents a wavelength, and its proportionality to interfiber separation follows from the geometric similarity of the construction of wave reflections. Such constructions are present in models of the acoustic resonance frequencies of simple enclosures (Beranek and Leo 1982).

The explanation offered here is that the hackle marks result from intense resonant vibrations of the matrix polymer cavity contained between the points of closest proximity of two adjacent fibers. These oscillations are considered to be so intense that the brittle matrix polymer is pulverized in regions surrounding the antinodes of these standing wave vibration modes. The shape of these hackle marks are therefore reflections of both the failure stress criterion and the intensity of vibration present in the composite during the impact event.

We consider that the hackle marks represent a significant augmentation of the surface area of a fragment and therefore also a correspondingly large store of surface free energy. We speculate that the spatial frequency must increase with the speed of impact, because our observations had been that the total energy absorbed (as measured by the decrease in kinetic energy of the projectile) increased with the velocity of the impact. A higher spatial frequency would represent an increase in surface area assuming the amplitude of the undulations remained constant. It is also conjectured that if the spatial frequency of the hackle marks did not increase with projectile speed, then perhaps the fractional coverage of the surface of a fragment

by hackle marks must reflect the increase in total impact energy absorbed. We are aware from the work of Grady (1982) at Sandia Laboratories of the decrease in the mean size of fragments produced as the strain rate is increased, which results in a greater density of the energy absorption per unit volume of the fractured and fragmented material. We have appropriated these results to the case of impact by postulating a proportionality between strain rate and projectile velocity. We now hypothesize that the hackle mark wavelength is a function only of the inter-fiber space occupied by matrix, and the distance between transverse matrix and their characteristic length is associated with the rate of impact event. We should continue to expect that the percentage coverage of the interply surface region by hackle marks should increase with the vehemence of the impact (that is, the strain rate or projectile arrival velocity) and that the amount of material missing from the region occupied by hackle marks should likewise increase with the applied intensity of the impact.

One must also expect that there may be a variation in the height of hackle marks relative to the distance from the impact face to the lamina in question. In the current study the fragment location relative to the impact surface was not determined.

CONCLUDING REMARKS

Initial results from ballistic impact tests have shown increased energy absorption at higher impact velocities. An analysis of the energy partitioning between various mechanisms of energy absorption is important in understanding the ballistic impact resistance of the material. Laminated

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plates have a unique failure mechanism in the ability to delaminate, which is the most favorable mode of failure for preventing penetration. This study has attempted to relate this energy to the micrographic features of the fractures on the delaminated surfaces to the energy level (velocity level). Fracture surfaces from fragments of high velocity (high strain rate) impact have shown a tendency to develop characteristic hackle marks. Their developments have been related to the cavity resonance of the matrix between the fibers. Although qualitative indications point to the existence of these phenomena, a quantitative analysis is still lacking.

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REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestion for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE December 1996	3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE

Ballistic Perforation of Graphite/Epoxy Composite

5. FUNDING NUMBERS

6. AUTHORS

Piyush K. Dutta, Dennis Farrell, Susan Taylor, Aziz Tadayon and David Hui

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER

Special Report 96-29

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of the Chief of Engineers
Washington, DC 20314-1000

U.S. Army Research Office
Research Triangle Park
North Carolina 27709

U.S. Air Force Flight Dynamics Laboratory
Wright-Patterson Air Force Base
Ohio 45433-7542

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES For conversion of SI units to non-SI units of measurement consult *Standard Practice for Use of the International System of Units (SI)*, ASTM Standard E380-93, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

Available from NTIS, Springfield, Virginia 22161.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

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14. SUBJECT TERMS

Ballistic tests, Composites, Dynamic fracture, Fracture, Graphite/epoxy, High-velocity impacts, Impact, Micrographs, Projectiles

15. NUMBER OF PAGES
10

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL